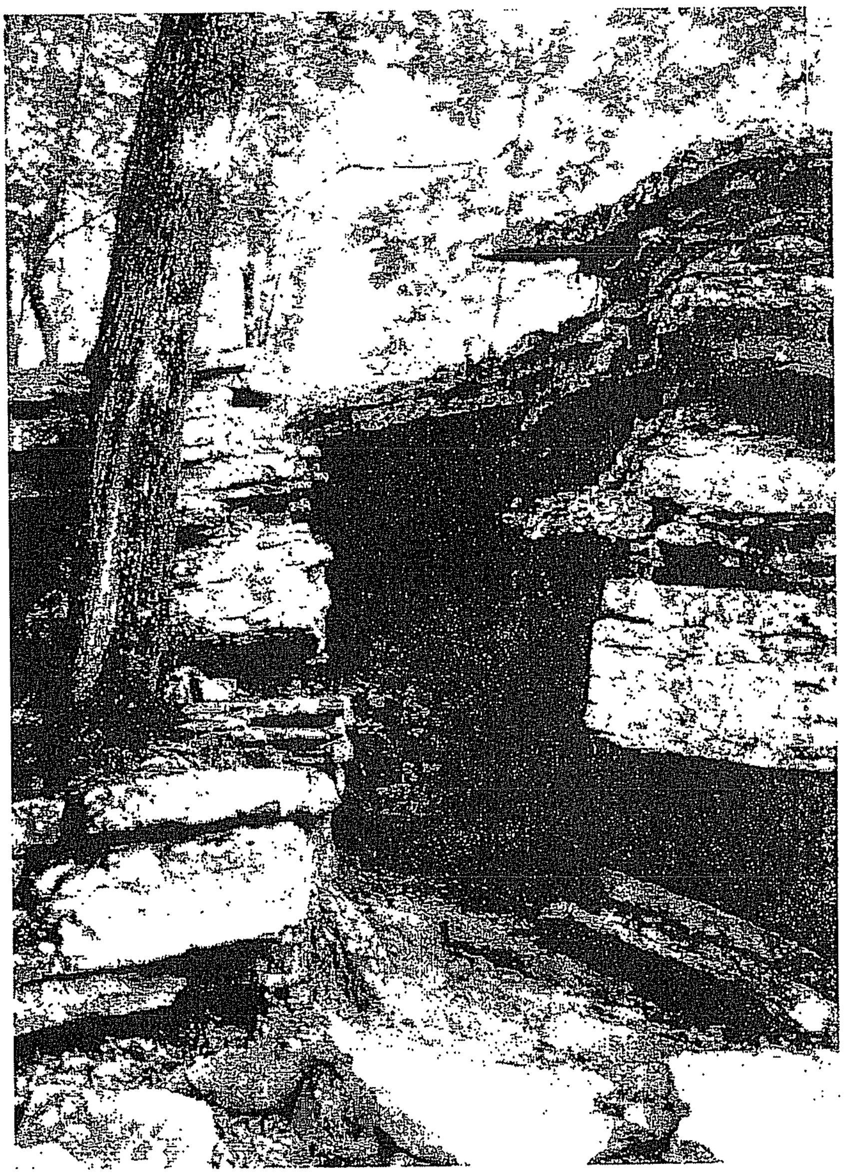
ENVIRONMENTAL AND HYDROLOGIC SETTING OF THE OZARK PLATEAUS STUDY UNIT, ARKANSAS, KANSAS, MISSOURI, AND OKLAHOMA

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 94-4022



NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

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by James C. Adamski, James C. Petersen, David A. Freiwald, *and* Jerri V. Davis

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Little Rock, Arkansas
1995

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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
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CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
acre	0.4047	hectare
square mile (mi^2)	2.590	square kilometer
foot per day (ft/d)	0.3048	meter per day
cubic foot per day (ft^3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06308	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
pound (lb)	0.4536	kilogram
foot square per day (ft^2/d)	0.09290	meter squared per day

Temperature in degrees Fahrenheit (° F) can be converted to degrees Celsius (° C) as follows:

$$°C = 5/9 \times (°F-32)$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Environmental and Hydrologic Setting of the Ozark Plateaus Study Unit, Arkansas, Kansas, Missouri, and Oklahoma

By James C. Adamski, James C. Petersen, David A. Freiwald, *and* Jerri V. Davis

ABSTRACT

The Ozark Plateaus study is 1 of 20 National Water-Quality Assessment (NAWQA) studies initiated by the U.S. Geological Survey in 1991 to describe the status and trends in the quality of the Nation's water resources. When the NAWQA program is fully implemented, a total of 60 study units in the United States will be investigated on a rotational basis. Study-unit investigations will include 5 years of intensive assessment activity followed by 5 years of low-level monitoring.

The environmental and hydrologic setting of the Ozark Plateaus National Water-Quality Assessment study unit and their factors that affect water quality are described in this report. The primary natural and cultural features that affect water-quality characteristics and the potential for future water-quality problems are described. These environmental features include physiography, climate, population, land use, water use, geology, soils, and surface- and ground-water flow systems.

The Ozark Plateaus study unit has an area of approximately 48,000 square miles and includes parts of Arkansas, Kansas, Missouri, and Oklahoma. The study unit contains most of the Ozark Plateaus Province and parts of the adjacent Osage Plains section of the Central Lowland Province and the Mississippi Alluvial Plain section of the Coastal Plain Province. The Ozark Plateaus Province consists of three sections--the Springfield Plateau, the Salem Plateau, and the Boston Mountains. Topography in the study unit is mostly gently rolling, except in the Boston Mountains and along the escarpment separating the Springfield and Salem Plateaus, where it is rugged. Karst features such as springs, sinkholes, and caves are common in the Springfield Plateau and abundant in the Salem Plateau.

The study unit has a temperate climate with average annual precipitation ranging from about 38 to 48 inches and mean annual air temperature ranging from 56 to 60 degrees Fahrenheit. Population in the study unit was about 2.3 million people in 1990 and increased 28 percent between 1970 and 1990. Land use in the study unit is predominantly pasture and cropland in the northwestern part, and forest and pasture in the southeastern part. Poultry farming is a major industry in the southwestern part of the study unit. Mining, primarily in the four major lead-zinc mining districts, has been an important part of the local economy in the past. Total water use averaged 1,053 million gallons per day in the study unit in 1990. Ground water accounted for about 58 percent of the water withdrawn for all uses; surface water accounted for 42 percent.

Basement igneous rocks of Precambrian age are overlain by as much as 5,000 feet of gently dipping sedimentary rocks throughout much of the study unit. The igneous rocks, which include granite, rhyolite, and diabase, are exposed only in the St. Francois Mountains of southeastern Missouri. The sedimentary rocks include rocks of Cambrian through Ordovician age, which consist of dolomite, sandstone, and limestone with minor amounts of shale; rocks of Mississippian age, which are mostly cherty limestones; rocks of Pennsylvanian age, which consist mostly of shale, sandstone, and limestone; and Post-Paleozoic sediments, which consist of sands, gravels, and clays. The igneous and sedimentary rocks that underlie the study unit are extensively fractured and

faulted. Alfisol and ultisol soil types underlie most of the study unit. These soils are moderately to deeply weathered and have a wide range of hydraulic properties.

All or part of seven major river basins are within the study unit. These basins include the White, Neosho-Illinois, Osage, Gasconade, Meramec, St. Francis, and Black River Basins. Many of the rivers are impounded to form reservoirs. Stream gradients are steepest in the Boston and St. Francois Mountains and least steep in the Osage Plains and Mississippi Alluvial Plain. Streambed material ranges from clay and silt in the Osage Plains to sand, gravel, boulders, and bedrock in most of the Ozark Plateaus Province. Mean annual runoff ranges from 9 to 10 inches in the Osage Plains to 14 to 20 inches in the Boston Mountains. Minimum monthly streamflows generally occur from July through October, and maximum monthly streamflows occur from March through May. Surface- and ground-water interactions are greatest in the Springfield and Salem Plateaus and least in the Boston Mountains and Osage Plains. The ionic composition of surface water generally is calcium or calcium magnesium bicarbonate in the study unit. Dissolved-solids concentrations in water from streams range from about 40 milligrams per liter in the Boston Mountains to as much as 280 milligrams per liter in the Osage Plains, but generally are less than 200 milligrams per liter. Streams in the Boston Mountains generally are the least mineralized and those in the Osage Plains generally are the most mineralized in the study unit.

The study unit contains eight hydrogeologic units that consist of three major aquifers--the Springfield Plateau, Ozark, and St. Francois aquifers--interbedded with four confining units. The unconsolidated sediments of the Mississippi Alluvial Plain are a very productive aquifer, but are of limited areal extent in the study unit. The Springfield Plateau and Ozark aquifers are formed from thick sequences of limestones and dolomites. Rocks in both of these aquifers have secondary porosity as a result of fracturing and dissolutioning and these aquifers are used extensively for sources of water supply. Where the Springfield Plateau aquifer is unconfined, it is extensively used as a source of water for domestic purposes. Well yields in this aquifer generally are less than 20 gallons per minute. The Ozark aquifer is used throughout much of the study unit as a source of water for public and domestic supply. Yields of wells completed in this aquifer commonly range from 50 to 100 gallons per minute but can be as much as 600 gallons per minute. The St. Francois aquifer consists of sandstones and dolomites of Cambrian age. Although well yields in this aquifer can be as much as 500 gallons per minute, the aquifer is rarely used except where it crops out. The ionic composition of ground water in most of the aquifers in the study unit is calcium or calcium magnesium bicarbonate, but locally it can be a calcium sulfate or sodium chloride where the aquifers are confined. Dissolved-solids concentrations generally range from 200 to 300 milligrams per liter, but can be as much as 10,000 milligrams per liter in the deeper aquifers along the western boundary. Ground water in the study unit has a pH of 5.2 to 8.3, locally can contain fecal bacteria, and in some areas has elevated concentrations of radionuclides and nitrates.

Factors that affect water quality in the study unit include geology, land use, and population density. The geochemical processes of mineral dissolution, ion exchange, and oxidation-reduction reactions are the dominant natural factors that affect water quality on a regional scale. Agricultural and mining land-use activities can increase the concentrations of nutrients, bacteria, dissolved solids, sulfate, and trace elements in the surface and ground water of the study unit. Increased population density can result in increased discharges of nutrients, trace elements, bacteria, suspended sediment, and organic compounds.

INTRODUCTION

Nationally consistent information on the status and trends of the Nation's water quality is needed to determine the degree to which past investments in water-quality management are working and to provide a base of knowledge for evaluating future decisions. In 1991, the U.S. Geological Survey (USGS) began to implement the full scale National Water-Quality Assessment (NAWQA) program to provide a nationally consistent description of water-quality conditions for a large part of the Nation's water resources. The long-term goals of the NAWQA program are to describe the status and trends in the quality of the Nation's surface- and ground-water resources and to provide a better understanding of the natural and human factors that affect the quality of these resources. Investigations will be conducted on a rotational basis in 60 river basins or aquifer systems (referred to as study units) throughout the Nation. Assessment activities began in 20 study units in 1991.

Regional and national synthesis of information from the study units will be the foundation for the comprehensive assessment of the Nation's water quality. Nationally consistent information on water quality, and factors such as climate, geology, hydrology, land use, and agricultural practices, will be integrated to focus on specific water-quality issues that affect large contiguous hydrologic regions. For example, an initial concern in the first 20 study units is the relation of the presence of pesticides in surface and ground water to application rates and cropping practices, and to climatic, geologic, and soil factors. Nutrients and sediment are also central problems to be addressed as part of the synthesis activities, which will contribute to answering fundamental national water-quality questions.

The study unit investigations will consist of 5 years (1991 to 1995) of intensive assessment activity, followed by 5 years (1996 to 2000) of low-level monitoring activity, and then the cycle is repeated. Within each 5-year intensive assessment activity period, there generally will be about 2 years of retrospective data analysis and planning, then 3 years of intensive-data collection (Leahy and others, 1990). The four main components of the intensive assessment activity and timeframe for the first 20 study units in the NAWQA Program are presented in table 1.

The retrospective analysis includes reviewing and analyzing existing hydrologic data to provide a historical perspective on water quality to aid in the design of the study unit intensive data-collection phase. The occurrence and distribution assessment will characterize the broad-scale geographic and seasonal distributions of water-quality conditions through sampling of surface- and ground-water resources and performing ecological surveys. Long-term monitoring will assess the status and trends of selected aspects of water-quality conditions. Case studies of sources, transport, and effects will address specific questions about water-quality changes related to specific contaminants in selected areas.

In 1991, the Ozark Plateaus study unit was among the first 20 NAWQA study units selected for study under the full-scale implementation plan. The complex, mostly karst aquifer system of the Ozark Plateaus study unit coupled with the influx of people and probability of future growth makes this area extremely susceptible to water-resources contamination. Four major water-quality issues were identified jointly by USGS personnel and representatives of various Federal, State, and local agencies in Arkansas, Kansas, Missouri, and Oklahoma that served on a coordination committee, the Ozark Plateaus NAWQA Liaison Committee. The recurring local or regional water-quality issues identified in the Ozark Plateaus study unit include problems associated with nutrients and bacteria, trace elements and dissolved solids, radionuclides in ground water, and saline ground-water encroachment.

Elevated levels of nitrate, ammonia, and bacteria in surface and ground waters have resulted from the expanding poultry, cattle, and swine industry in northern Arkansas and southern Missouri. Arkansas is the leading poultry producer, and Missouri is the second leading producer of beef cattle in the United States.

Lead, zinc, and other trace elements are present in surface and ground waters in part of the Ozark Plateaus study unit, as a result of mining activities. Missouri has been a leading producer of lead and zinc ore in the United States since the 1800's. Numerous abandoned lead and zinc mines that are now flooded are located in southwestern Missouri, southeastern Kansas, and northeastern Oklahoma. Water in these mines typically contains higher than normal concentrations of trace elements and dissolved solids. Lead mining of the Viburnum Trend or New Lead Belt of southeastern Missouri is expected to continue at present levels to the year 2000.

Naturally occurring radioactivity (radium-226 and -228) in ground water in excess of the maximum contaminant levels (MCL's) established for drinking water by the U.S. Environmental Protection Agency has been detected in the Ozark aquifer. Radionuclides are present primarily along the saline-freshwater transition zone on the western boundary of the Ozark Plateaus in Kansas, Missouri, and Oklahoma; St. Francois

Table 1. Timeframe of National Water-Quality Assessment program intensive assessment activity for the first 20 study units

Activity	Fiscal year (October through September) 1991	1992	1993	1994	1995
Retrospective Analysis and Planning					
Retrospective Data Analysis					
Water-Quality Reconnaissance					
Occurrence and Distribution Assessment					
SURFACE WATER					
Bed Sediment and Tissues					
Occurrence Survey					
Spatial Distribution Survey					
Water Column					
Basic Fixed Stations					
Intensive Fixed Sites					
Synoptic Studies					
ECOLOGY					
Ecological Survey Prototype					
Ecological Survey					
GROUND WATER					
Study-Unit Survey					
Land-Use Studies					
Flowpath Studies					
Long-term Monitoring					
Case Studies of Sources, Transport, and Effects					
	1991	1992	1993	1994	1995

County in Missouri; and Newton and Searcy Counties in Arkansas.

The saline-freshwater transition zone lies along the entire western boundary of the study unit in the Ozark Plateaus aquifer system. The use of ground water near this transition zone has caused water levels to decline from 100 to 300 ft in places and has induced movement of highly saline ground water from the west into some well fields, resulting in ground water from these well fields that may be unsuitable for many uses.

Purpose and Scope

The purpose of this report is to describe the environmental and hydrologic setting of the Ozark Plateaus study unit and the factors that affect water quality. This report is the first in a series of NAWQA reports on the Ozark Plateaus study unit. It is intended to be used as a general reference for the environmental setting of the study unit and as background information for subsequent in-depth topical reports on water quality and aquatic biology.

The report describes the climate, physiography, geology, soils, population, land use, water use, and surface- and ground-water systems in the study area. Factors that affect surface- and ground-water quality are described for the primary natural and cultural environmental features of climate, physiography, geology, soils, population, land use, and water use. These environmental features largely determine water-quality characteristics and the potential for future water-quality issues in the area. Only a brief description of selected water-quality characteristics is included in this report.

Location

The Ozark Plateaus study unit area is approximately 48,000 mi^2 and includes parts of four States: northern Arkansas, southeastern Kansas, southern Missouri, and northeastern Oklahoma (fig. 1). The study unit includes most of the about 40,000 mi^2 Ozark Plateaus Province as well as parts of the surrounding Central Lowland Province known as the Osage Plains section, and a small part of the Mississippi Alluvial Plain section of the Coastal Plain Province. The study-unit boundary approximates the natural flow boundaries of the Ozark Plateaus aquifer system (Imes and Emmett, 1994) but has been truncated on the north, east, and south to include only those major hydrologic units that exist in the core of the Ozark Plateaus Province. The western study-unit boundary extends beyond the Ozark Plateaus physiographic province to include the complex ground-water transition zone where fresh ground water from the Ozark Plateaus mixes with saline ground water from the Western Interior Plains aquifer system (Imes and Emmett, 1994). The northern boundary of the Ozark Plateaus study unit coincides with the northern boundaries of the Osage, Gasconade, and Meramec Rivers hydrologic unit boundary. The eastern boundary of the study unit coincides with the eastern boundaries of the Meramec and upper St. Francis River hydrologic unit boundary. The southeastern boundary of the study unit coincides with the eastern boundary of the Black River hydrologic unit boundary. The southern boundary of the study unit coincides with the drainage divide in the Boston Mountains.

Previous Investigations

The NAWQA program concepts and plans are described in reports by Hirsch and others (1988) and Leahy and others (1990). The water-quality issues, objectives, and approach for this study have been described by Freiwald (1991).

Numerous hydrologic or environmental investigations of all or parts of the Ozark Plateaus region have been made in the past. Climatic information, mostly relating to precipitation in the study unit, has been described by Dugan and Peckenpaugh (1985) and Freiwald (1985). Information on temperature and potential evapotranspiration has been published by Dugan and Peckenpaugh (1985) and Hanson (1991). Physiography of the area has been described by Fenneman (1938). Population data from the 1990 census have been published for individual states by the U.S. Department of Commerce, Bureau of Census (1990). Land use in the study unit has been described by Rafferty (1980) and Dugan and Peckenpaugh (1985). Geologic investigations in the study unit include those by Snider (1915) in northeastern Oklahoma; Howe and Koenig (1961) in Missouri; and Croneis (1930), Caplan (1957; 1960), and Frezon and Glick (1959) in northern Arkansas.

The Central Midwest Regional Aquifer-System Analysis (CM RASA) study completed in 1985 investigated the geohydrology of the Ozark Plateaus Province and adjacent areas, and provided much of the geologic and hydrogeologic foundation for this report (Jorgensen and Signor, 1981). In that study, Imes and Emmett (1994) identified the major geohydrologic units in the Ozark Plateaus, described the regional factors that control ground-water flow, and constructed a digital ground-water flow model of the Ozark Plateaus aquifer system. A series of map reports on the major aquifers and confining units in the Ozark Plateaus were produced by Imes (1990a-g). These reports describe the outcrop area, structure, thickness, potentiometric surface, and dissolved solids concentration of water in the aquifer, and percentage shale in the confining units. Also in this map series are reports by Imes and Davis (1990a, b; 1991), which describe water type, and concentration of dissolved solids, chloride, and sulfate in water from the St. Francois, Ozark, and Springfield Plateau aquifers.

A general summary of the hydrology of aquifers in the Springfield and Salem Plateaus of southern Missouri and northern Arkansas is presented in Harvey (1980). Christenson and others (1990) described the geology, hydrology, and water quality of the Roubidoux aquifer in northeastern Oklahoma. Lamonds (1972) described the occurrence, availability, and chemical quality of ground and surface water for the Ozark Plateaus of northern Arkansas. The hydrology and geochemistry of the lead-zinc mined areas of Cherokee County, Kansas, and adjacent areas are described by Spruill (1987).

Runoff and streamflow characteristics for Ozark Plateaus streams are presented in a report by Hedman and others (1987). Gann and others (1974; 1976) presented a general summary of information about the occurrence, availability, use, and quality of water in that part of Missouri south of the Missouri River. Information on major streams and reservoirs in Missouri have

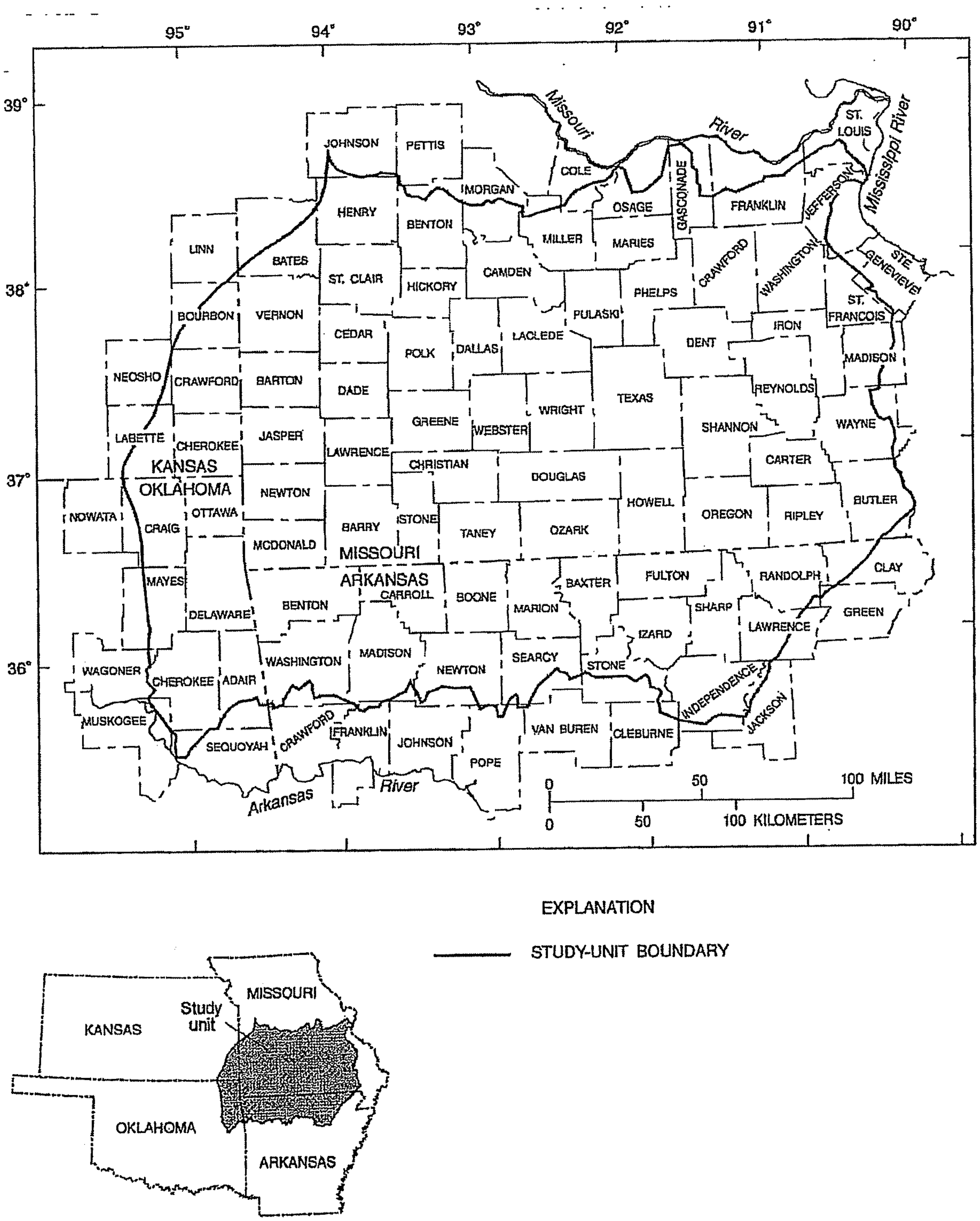


Figure 1. Ozark Plateaus National Water-Quality Assessment study unit location.

been described by Homyk and Jeffery (1967), U.S. Army Corps of Engineers (1967), Duchrow (1984), and Pflieger (1989). Information on surface-water quality has been presented in reports by Lamonds (1972), Gann and others (1974; 1976), Stoner (1981), Bennett and others (1987), Petersen (1988), Davis and Howland (1993), Petersen and others (1993), Kurklin and Jennings (1993), and Kenny and Snethen (1993).

ENVIRONMENTAL SETTING

Climate

The Ozark Plateaus study unit has a temperate climate because of its mid-latitude, interior-continent location. Major weather systems normally move from west to east during the fall, winter, and spring seasons. In early spring, the study unit receives moisture-laden air from the Gulf of Mexico, which often results in thunderstorms, tornadoes, and intense rainfall. Thunderstorms are responsible for most of the severe weather in the study unit. The severe weather season extends from March through June, although thunderstorms can occur throughout the year and occasionally cause flash floods.

Average annual precipitation generally increases toward the southeast from about 38 in/yr (inches per year) in the northern part of the study unit to about 48 in/yr near the southern boundary (fig. 2). Average seasonal precipitation during the cool season (October through March) ranges from around 12 in. in the northwestern part of the study unit to 24 in. in the southeastern part. Average precipitation during the warm season (April through September) ranges from 22 in. in the northeastern part of the study unit to 26 in. in the southwestern part (Dugan and Peckenpaugh, 1985). Average monthly precipitation indicates a seasonal pattern (fig. 3). Precipitation generally is greatest in the late spring (April to June) and least in late winter (December to February).

Mean annual air temperature ranges from 56 °F in the northeastern part of the study unit to 60 °F in the southwestern part (fig. 4). Mean monthly temperatures generally are lowest in January and highest in July. The mean temperature during January ranges from 30 °F in the northern part of the study unit to 38 °F in the southern part. The mean temperature during July ranges from 78 °F along the eastern boundary of the study unit to about 82 °F along the southwestern boundary. The seasonal variation in mean temperatures is closely related to seasonal solar radiation with greater regional contrasts in winter than in summer. Also, the polar front and jet stream normally pass through the study unit in winter causing increased temperature contrasts within the study unit (Dugan and Peckenpaugh, 1985).

The estimated mean annual evapotranspiration rate in the study unit is 30 to 35 in/yr. Seasonal trends in evapotranspiration follow the seasonal trends in air temperature and solar radiation; the maximum rate occurs during the summer, and the minimum rate occurs during the winter. Evapotranspiration fluctuates daily as well as seasonally. In clear weather, the rate increases through the morning and reaches a maximum in early to midafternoon (Hanson, 1991).

Precipitation in the study unit generally is acidic with low dissolved-solids concentrations. In 1990, the pH of precipitation ranged from about 4.6 to 5.0, and the sum of the major cations--calcium, magnesium, sodium, and potassium--was less than 0.5 mg/L (milligram per liter; National Atmospheric Deposition Program, 1991).

Physiography

The Ozark Plateaus study unit includes most of the Ozark Plateaus Province and small parts of the Osage Plains and Mississippi Alluvial Plain of the Central Lowland and Coastal Plain Provinces, respectively (fig. 5). These three major physiographic provinces include a diverse range of topography and geomorphology, which greatly affects the hydrology of the area. Altitudes in these provinces range from greater than 200 ft in the Mississippi Alluvial Plain to more than 2,300 ft in the Boston Mountains.

Ozark Plateaus Province

The Ozark Plateaus Province has an area of about 40,000 mi^2 and includes parts of four states. The physiography of this province is largely controlled by the geology of the area; a structural dome underlies most of the province. Sedimentary rocks of Paleozoic age flank a core of igneous rocks at the center of the structural dome in southeastern Missouri. The igneous rocks form the St. Francois Mountains. The sedimentary rocks, which dip gently away from the center of the dome, form three distinct physiographic sections--the

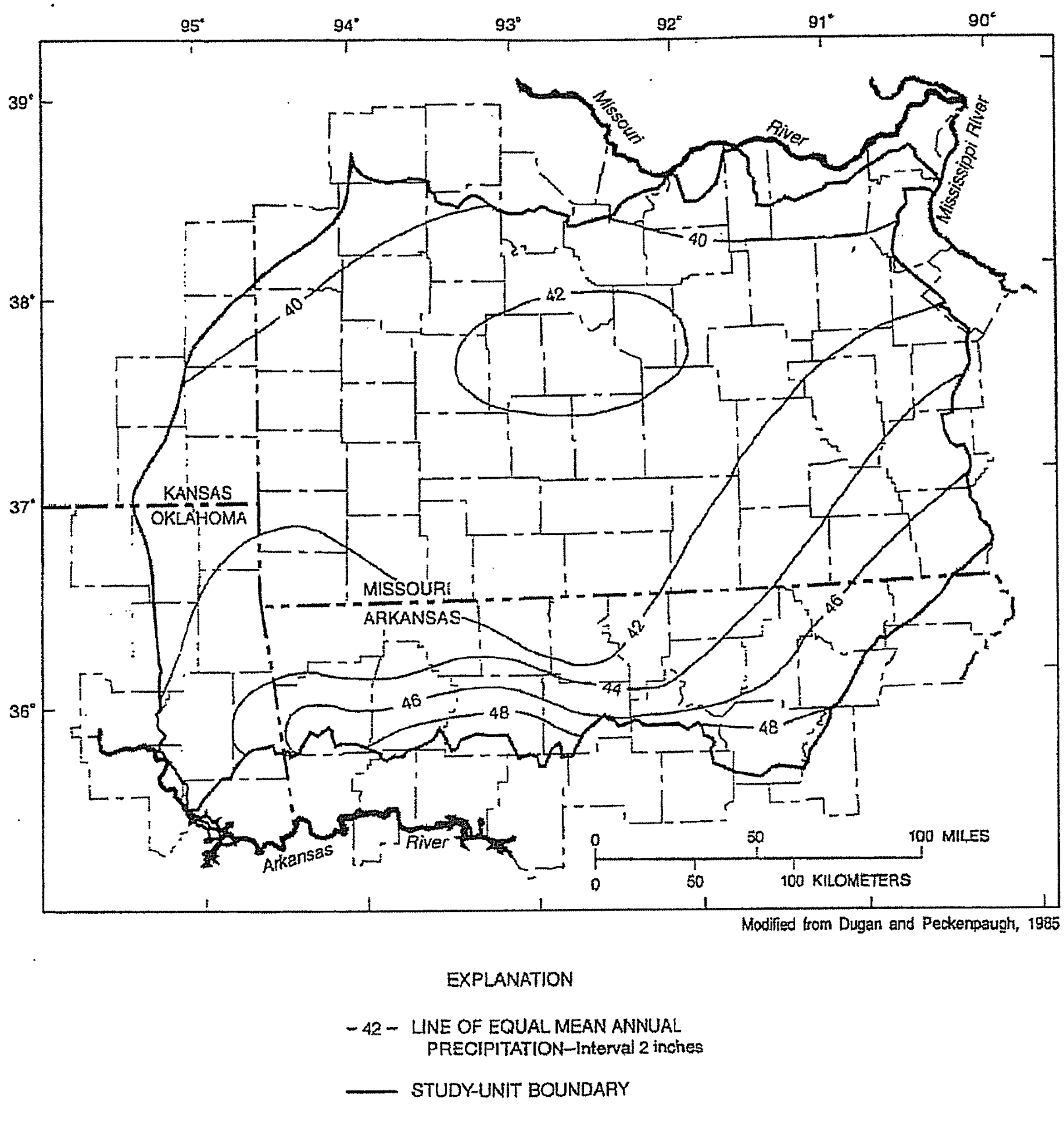
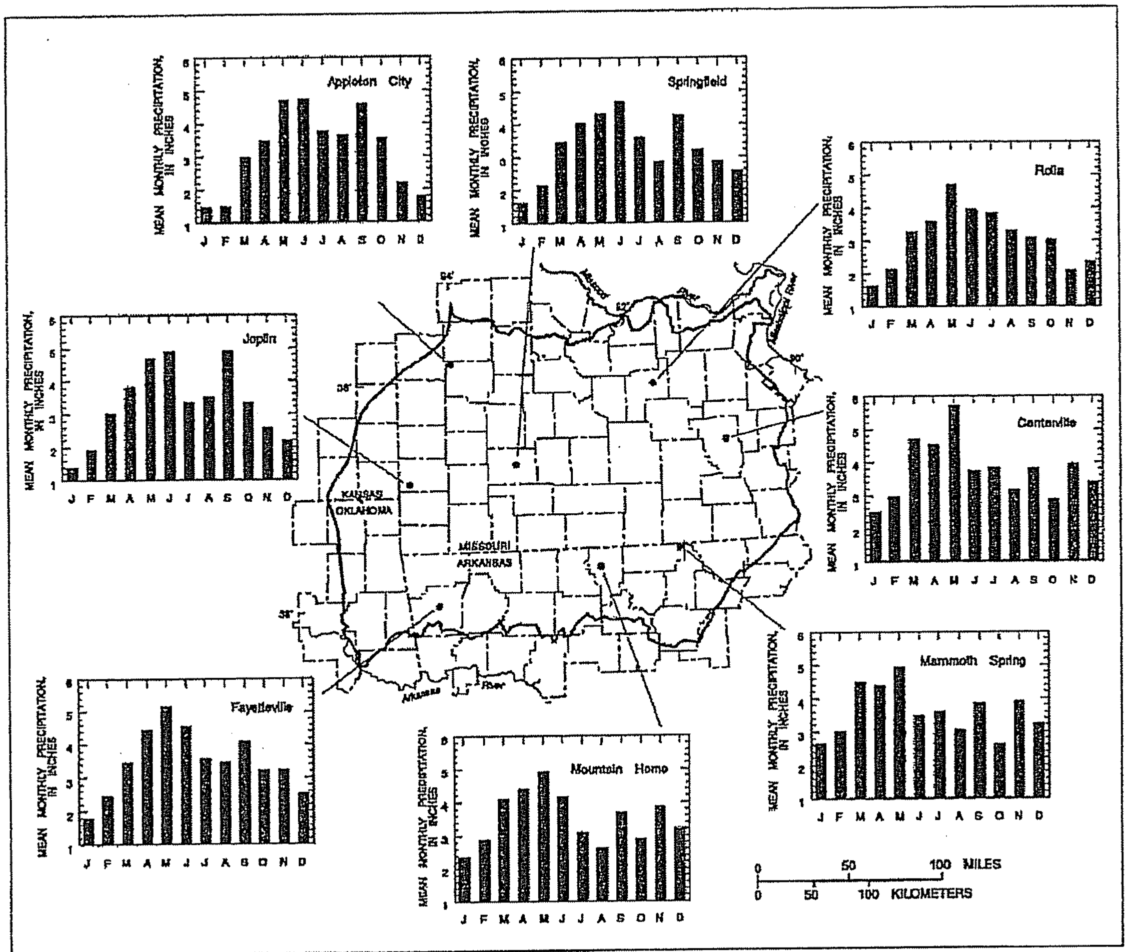


Figure 2. Mean annual precipitation in the Ozark Plateaus study unit, 1951-80.



Data from U.S. Department of Commerce, National Ocean and Atmospheric Administration, 1990

EXPLANATION

—— STUDY-UNIT BOUNDARY

• LOCATION OF CITY

Figure 3. Mean monthly precipitation for selected cities in the Ozark Plateaus study unit, 1951-80.

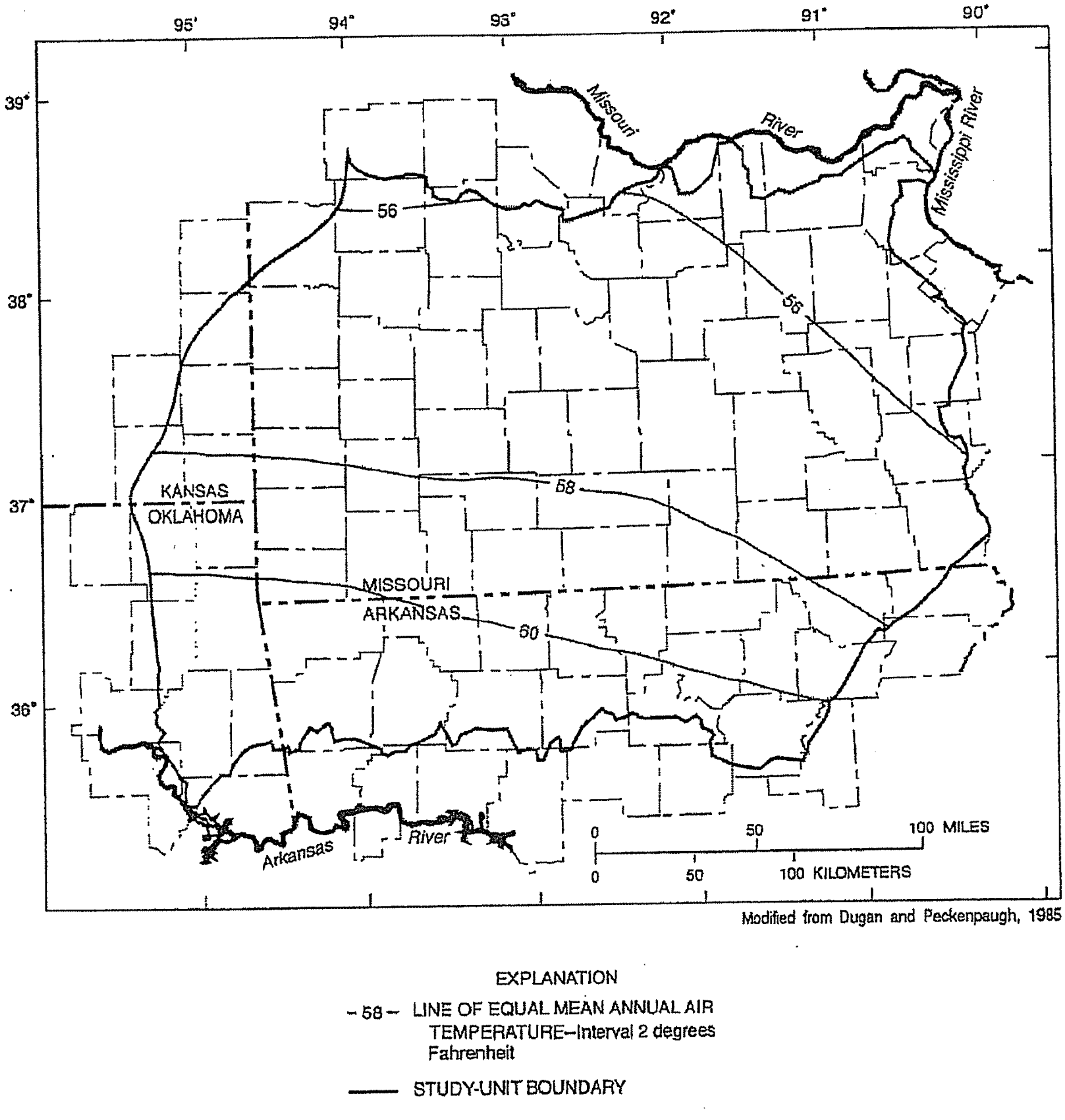


Figure 4. Mean annual air temperature in the Ozark Plateaus study unit, 1951-80.

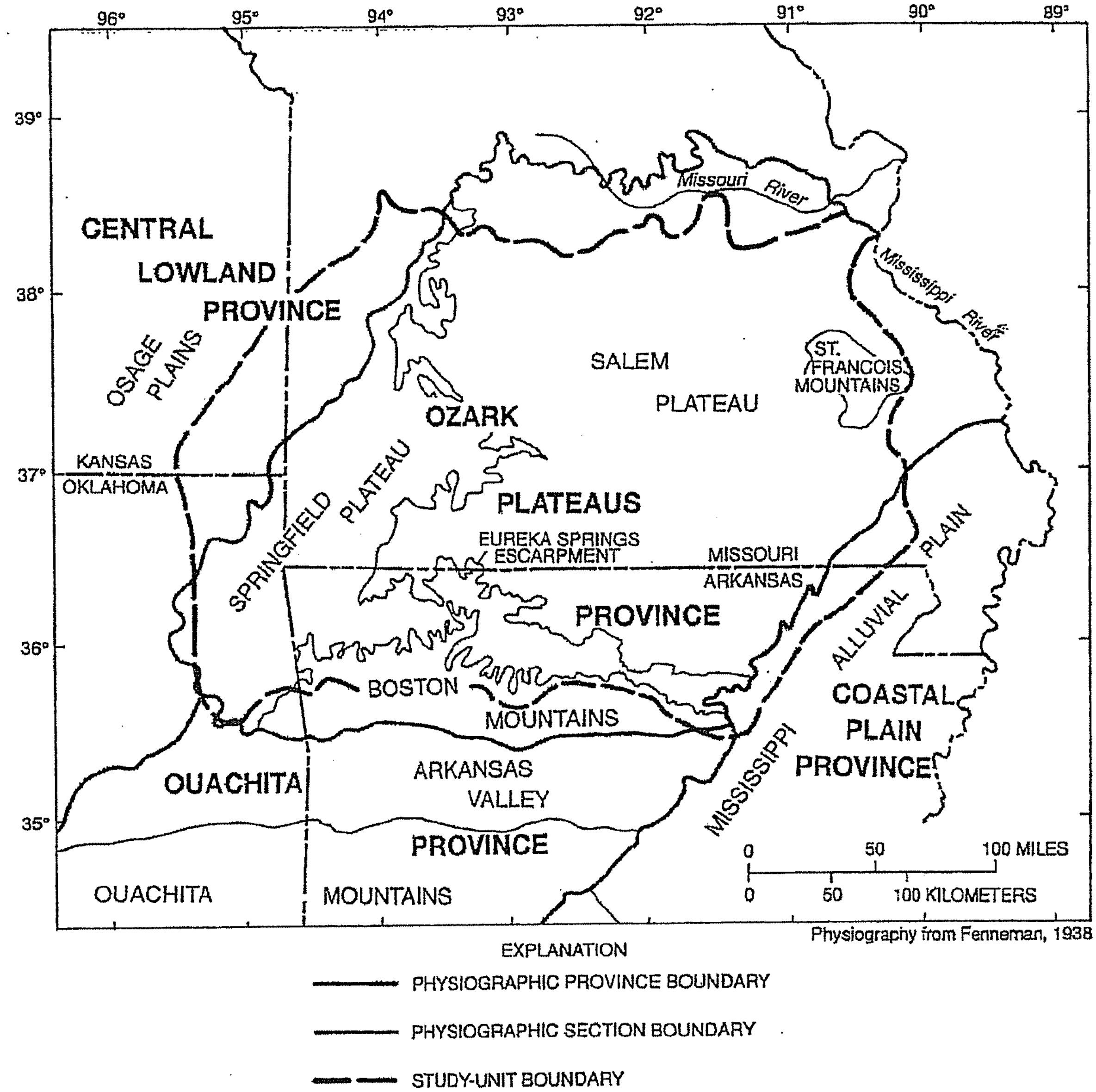


Figure 5. Physiographic subdivisions of the Ozark Plateaus study unit and adjacent areas.

Springfield Plateau, the Salem Plateau, and the Boston Mountains (Fenneman, 1938). In this report, each of these sections generally will be referred to without the physiographic section nomenclature. For example, the Salem Plateau section will be referred to as the "Salem Plateau."

The southeastern boundary of the Ozark Plateaus Province is marked by the contact between rocks of Paleozoic age of the Ozark Plateaus and younger, unconsolidated sediments of the Mississippi Alluvial Plain. The southern boundary is marked by faults on the southern flank of the Boston Mountains, although the southern boundary of the study unit is the east-west trending drainage divide formed by the Boston Mountains. The western boundary of the province is marked by the contact between rocks of Mississippian and Pennsylvanian age. The northern and eastern boundaries of the province generally follow the Missouri and Mississippi Rivers, respectively. However, an area containing rocks of Devonian age and older exposed in Illinois and structurally a part of the Ozark Plateaus Province (Fenneman, 1938) is not included as part of the study-unit area.

The highest land surface altitude in the study unit outside the Boston Mountains is 1,772 ft above sea level at Taum Sauk Mountain in the St. Francois Mountains. A ridge of locally high relief extends west-southwest from the St. Francois Mountains to the extreme southwestern corner of Missouri. Altitudes along this ridge range from 1,200 ft to more than 1,600 ft above sea level. Altitudes generally decrease to the northwest and south of this ridge (Fenneman, 1938).

Topography in the province ranges from nearly flat-lying to rugged. The boundaries between each plateau are characterized by escarpments where deeply incised valleys separate narrow divides or "mountains." The result is rugged topography with relatively high relief. Away from the escarpments, topography is nearly flat-lying to gently rolling hills with low relief. The exception is the Boston Mountains, which has rugged topography nearly everywhere (Fenneman, 1938).

Stream drainage patterns are radial, away from regional and local topographic highs. Drainage patterns can follow geologic features such as faults and joints in the rocks. Entrenched meanders, resulting from the downcutting of streams as the area was uplifted, are common in the larger stream valleys.

The Ozark Plateaus Province contains numerous distinctive geomorphic features. The development of these features generally is related to the geology and hydrology of the area. For example, local topographic highs can form two distinct geomorphic features--mounds and bald mountains. Mounds are erosional remnants of outliers of rocks of Mississippian or Pennsylvanian age overlying older sedimentary rocks. Bald mountains, commonly called "balds," are predominantly tree-less hills present in south-central Missouri. Lines of trees on bald mountains can indicate water-bearing fractures in the rock (Beveridge and Vineyard, 1990).

Karst features are common in the Ozark Plateaus. Dissolution of carbonate rocks along fractures and faults has produced cave systems, sinkholes, and natural tunnels in the area (Beveridge and Vineyard, 1990). Missouri alone contains at least 5,000 caves, most of which are located in the Ozark Plateaus Province (Missouri Department of Natural Resources, 1980).

Filled paleo-sinkholes sometimes contain, and were mined for, iron, lead, and zinc ores. One of the largest of these filled sinkholes is the Oronogo Circle in Jasper County, Missouri. This sinkhole is 1,000 ft in diameter, and has been mined to depths as much as 190 ft deep (Beveridge and Vineyard, 1990).

Salem Plateau

The Salem Plateau includes a large part of the study unit (approximately 27,200 mi^2) in Missouri and northern Arkansas (fig. 5). It is underlain by rocks of Cambrian and Ordovician age. The Salem Plateau contains a central upland area, which is present west of the St. Francois Mountains in Dallas, Laclede, Polk, Webster, and Wright Counties, Missouri (fig. 1). The upland generally is characterized by gently rolling hills. Local relief in the upland area is 50 to 100 ft (Fenneman, 1938).

Away from the upland area, the plateau is dissected by numerous streams, which results in increased relief. South and east of the upland, topography is rugged, and relief can be as much as 500 ft. North of the upland, topography is rugged, but relief rarely exceeds 350 ft (Fenneman, 1938).

Sinkholes and springs are abundant in the Salem Plateau. On average, the upland area has 1 to 10 sinkholes per 100 mi^2 (fig. 6). A north-south trending band in south-central Missouri contains more than 10 sinkholes per 100 mi^2 (Harvey, 1980). Large springs with discharges exceeding 100 ft^3/s are common in some areas of the Salem Plateau (Imes and Smith, 1990).

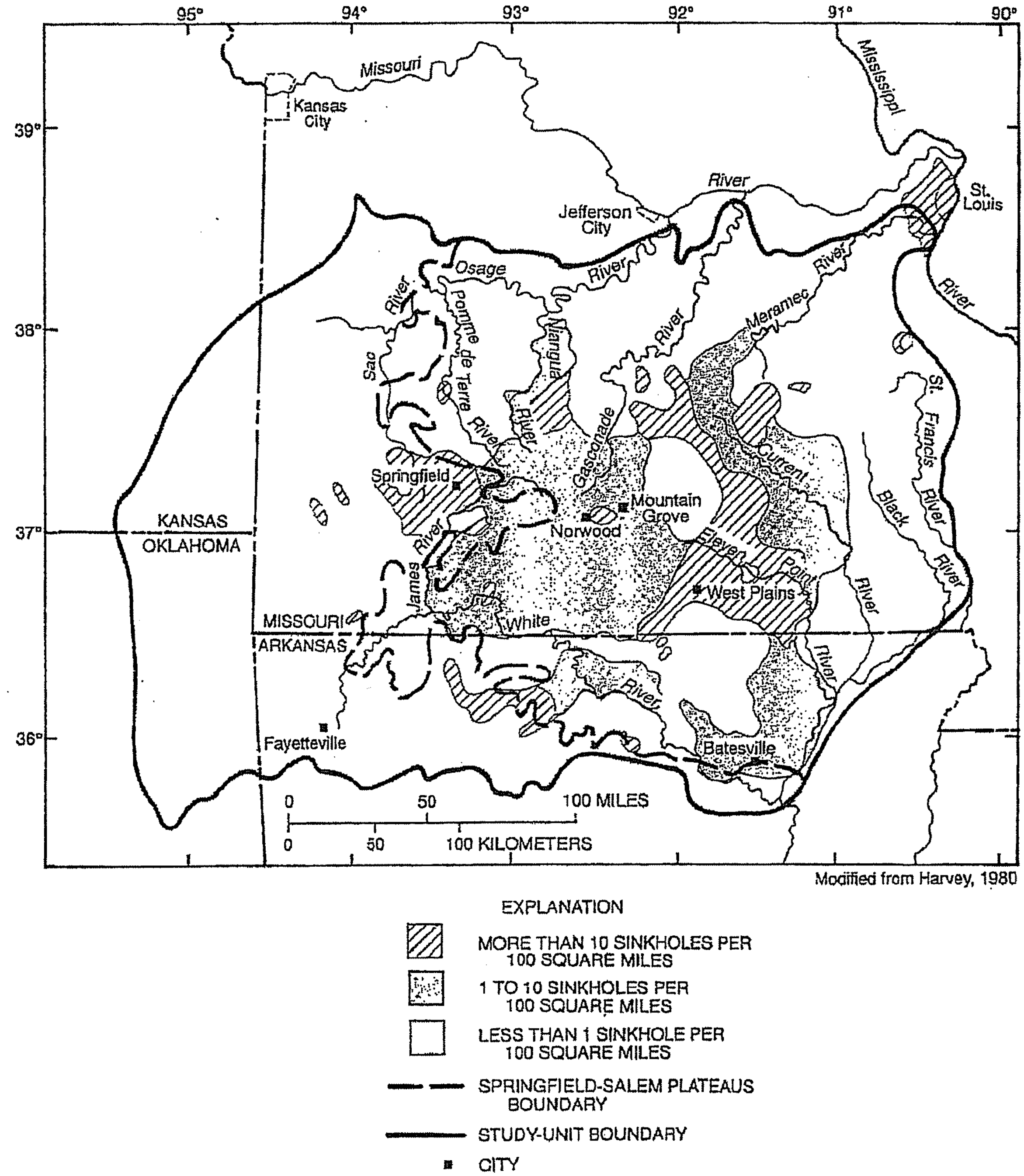


Figure 6. Distribution of sinkholes in southern Missouri and northern Arkansas.

The St. Francois Mountains are within the Salem Plateau and are formed from exposures of igneous rocks of Precambrian age associated with the structural dome in southeastern Missouri. The St. Francois Mountains are a series of resistant hills or knobs separated by valleys that are underlain by sedimentary rocks of Cambrian age. The St. Francois Mountains occupy an area of approximately 1,350 mi^2, but the area in which predominantly igneous rocks are exposed is less than 100 mi^2 (Fenneman, 1938). Land surface altitudes range from 1,000 to more than 1,700 ft above sea level. Topography is rugged and relief ranges from 500 to 800 ft (Fenneman, 1938). The St. Francois Mountains are not a separate physiographic section as defined by Fenneman (1938), but will often be discussed in this report separately because of its unique geological features, which affect the hydrology of the area.

Springfield Plateau

The Springfield Plateau occupies an area of approximately 10,300 mi^2 in the study unit including parts of west-central and southwestern Missouri, southeastern Kansas, northeastern Oklahoma, and northern Arkansas (fig. 5). The Plateau is underlain by limestones and cherty limestones of Mississippian age (Fenneman, 1938).

Land-surface altitudes in the Springfield Plateau range from 1,000 to 1,700 ft, but locally topographic relief, which decreases from east to west, rarely exceeds 200 to 300 ft. Topography is mostly gently rolling hills, except at the Eureka Springs Escarpment (fig. 5), which separates the Springfield and Salem Plateaus, where deeply incised stream valleys separate narrow divides (Fenneman, 1938).

Sinkholes and springs are common in the Springfield Plateau, but generally are smaller and less abundant there than in the Salem Plateau. The number of sinkholes in the Springfield Plateau generally averages less than 1 per 100 mi^2 except near the city of Springfield, Missouri, where there are more than 10 sinkholes per 100 mi^2 (fig. 6).

Boston Mountains

The Boston Mountains occupy an area of approximately 2,400 mi^2 in a 200-mi wide band extending through northern Arkansas and northeastern Oklahoma (fig. 5). They are underlain by sandstones, shales, and limestones of late Mississippian to Pennsylvanian age. Land-surface altitudes in the Boston Mountains range from 1,200 to more than 2,300 ft above sea level. Topographic relief is as much as 1,000 ft in some places. The topography is rugged, with narrow divides separating steep-sided valleys (Fenneman, 1938).

Central Lowland and Coastal Plain Provinces

The Central Lowland Province occupies a large area in the central United States extending from Texas to North Dakota and from Missouri to Colorado (Fenneman, 1938). The Osage Plains section of this province includes an area in the western and northwestern part of the study unit.

The Coastal Plain Province is another extensive province, extending along the Atlantic and Gulf Coasts from New England to Texas. It is a continuation of the Continental Shelf and has a very gentle slope. The Mississippi Alluvial Plain section of this province, which is an area of delta and bottomlands of the Mississippi River and tributaries (Fenneman, 1938), includes a small area in the southeastern part of the study unit.

Osage Plains

The Osage Plains occupies an area of approximately 6,700 mi^2 in the western and northwestern part of the study unit (fig. 5). The Osage Plains is underlain by soft shales with interbedded sandstones and limestones of late Mississippian to Pennsylvanian age. Land-surface altitudes in the part of the study unit in the Osage Plains range from 800 to 1,000 ft. In general, topography in this part of the study unit consists of gently rolling hills, but in some areas resistant beds of sandstones and limestones form rare east-facing escarpments (Fenneman, 1938).

Mississippi Alluvial Plain

The Mississippi Alluvial Plain includes a small area of approximately 1,100 mi^2 in the southeastern part of the study unit (fig. 5). The Mississippi Alluvial Plain is a flat to gently-rolling plain underlain by unconsolidated sediments of Cretaceous through Quaternary age. Land-surface altitudes in the part of the study unit in the Mississippi Alluvial Plain average just over 200 ft above sea level and topographic relief seldom exceeds 30 ft.

The formation of the plains is partially structural and partially erosional. The boundary between the unconsolidated sediments of the Mississippi Alluvial Plain and sedimentary rocks of Paleozoic age is formed by normal faults. Faulting has resulted in subsidence of the older sedimentary rocks, allowing a thick sequence of unconsolidated sediments to be deposited on top. The Mississippi River and its tributaries have eroded the unconsolidated sediments in places, forming occasional bluffs and ridges in the section (Fenneman, 1938).

Geologic Setting

The geology of the Ozark Plateaus study unit is diverse in lithology, mineralogy, and structure. Lithologies include igneous and sedimentary rocks. Secondary mineralization has occurred in many of the rock units, and uplifting has resulted in fracturing and faulting of the rock units.

Stratigraphy

The stratigraphy of the Ozark Plateaus study unit is complex. The basement crystalline rocks in the study unit are overlain by a sequence of sedimentary rocks of Paleozoic age (fig. 7). The sedimentary-rock sequence consists predominantly of dolomites and limestones of Cambrian through Mississippian age in some areas and sandstones and shales of Pennsylvanian age in other areas. In addition, lateral changes in lithology, the absence of some geologic units in parts of the study unit, and nomenclature, which has evolved independently in the four states, result in different stratigraphic sequences over the study unit (Imes and Emmett, 1994). These units are briefly described in the following section.

Precambrian Units

Igneous and metamorphic rocks of Precambrian age underlie the Ozark Plateaus and crop out in several places in the eastern part of the study unit (fig. 8). Elsewhere, these rocks are buried under as much as 5,000 ft of sedimentary rock. Structural relief of the rocks can be as much as 1,000 ft in a few miles (Imes and Emmett, 1994). These igneous rocks are mainly felsic (silica rich) rocks such as granite and rhyolite with mafic (silica poor) intrusions consisting of diabase and gabbro (Kisvarsanyi, 1981). Felsic rocks contain minerals such as quartz and potassium feldspar, which are resistant to weathering. In contrast, the mafic rocks contain minerals such as pyroxene and calcium plagioclase, which weather easily.

The igneous rocks of Precambrian age also contain commercially important quantities of several trace elements, including iron, lead, manganese, and silver (Kisvarsanyi, 1981). In addition, uranium and thorium are present in some of these rocks (primarily the granites) in concentrations as large as 34 and 54 mg/kg (milligrams per kilogram), respectively (Kisvarsanyi, 1987).

Cambrian and Ordovician Units

Rocks of Cambrian and Ordovician age in the study unit crop out mainly in the Salem Plateau (fig. 8). The geologic units of Cambrian and Ordovician age range in thickness from less than 50 ft to more than 4,000 ft; and average about 2,000 ft thick (Imes, 1990b, c, d). In general, the units consist predominantly of dolomites, cherty dolomites, sandstones, and limestones (Caplan, 1960), although shales are present in some areas mainly as discontinuous beds and thin partings.

The basal unit of the Cambrian and Ordovician rocks, the Lamotte Sandstone of Late Cambrian age, rests unconformably on igneous rocks of Precambrian age. It is a well-sorted quartz sandstone, which is arkosic and conglomeratic at its base. Its thickness ranges from less than 50 ft to nearly 500 ft. The Lamotte Sandstone grades upward into the Bonneterre Dolomite or equivalent, which is also of Cambrian age (Caplan, 1960).

The Bonneterre Dolomite is a fine- to medium-grained dolomite that crops out in the vicinity of the St. Francois Mountains. It contains glauconite and pyrite, and it can contain locally minor amounts of chert and shale. It is 200 to 300 ft in thickness near the St. Francois Mountains, but the thickness decreases southward to about 70 ft in northern Arkansas (Caplan, 1960). In southeastern Missouri, the Bonneterre Dolomite is extensively mineralized, containing abundant lead- and zinc-sulfide deposits. Other trace elements, such as cobalt, copper, nickel, and silver, are present in lower concentrations in the Bonneterre Dolomite (Wharton and others, 1975).

The Davis Formation and Derby-Doe Run Dolomite are shaly to silty, glauconitic dolomites that crop out in a roughly circular band around the St. Francois Mountains (Caplan, 1960). Thickness of the Davis Formation near its type locality is about 160 ft; thickness of the Derby-Doe Run Dolomite is about 115 ft (Howe

ERATHEM	SYSTEM	SOUTHERN MISSOURI	SOUTHEASTERN KANSAS	NORTHEASTERN OKLAHOMA	NORTHERN ARKANSAS	HYDROGEOLOGIC UNIT	HYDROGEOLOGIC SYSTEM
		Post-Paleozoic sediments					
PALEOZOIC	PENNSYLVANIAN	Kansas City Group Pleasanton Formation Marmaton Group Cherokee Shale	Kansas City Group Pleasanton Group Marmaton Group Cherokee Group	Marmaton Group Cabaniss Group Krebs Group Atoka Formation Bloyd Shale Hale Formation	Atoka Formation Bloyd Shale Hale Formation		Western Interior Plains confining system
	MISSISSIPPIAN	Fayetteville Shale Batesville Sandstone Hindsville Limestone Carterville Formation		Pitkin Limestone Fayetteville Shale Batesville Sandstone Hindsville Limestone	Pitkin Limestone Fayetteville Shale Batesville Sandstone		
		St. Louis Limestone Salem Limestone Warsaw Limestone Keokuk Limestone Burlington Limestone Elsey Formation Reeds Spring Limestone Pierson Formation	St. Louis Limestone Salem Limestone Warsaw Limestone Keokuk Limestone Burlington Limestone Fern Glen Limestone	Moorefield Formation	Moorefield Formation		
				Keokuk Limestone Boone Formation St. Joe Limestone	Boone Formation St. Joe Limestone	Springfield Plateau aquifer	Ozark Plateaus aquifer system

Figure 7. Geologic and hydrogeologic units in the Ozark Plateaus study unit and adjacent areas (modified from Imes, 1990a).

PALEOZOIC	MISSISSIPPIAN	Northview Shale Sedalia Limestone Compton Limestone	Chouteau Limestone	Northview Equivalent Compton Equivalent		Ozark confining unit	Ozark Plateaus aquifer system
	DEVONIAN	Chattanooga Shale	Chattanooga Shale	Woodford Chert Chattanooga Shale	Chattanooga Shale		
		Callaway Formation Fortune Formation		Sallisaw Formation Frisco Limestone	Clifty Limestone Penters Chert	Ozark aquifer	
	SILURIAN			St. Clair Limestone	Lafferty Limestone St. Clair Limestone Brassfield Limestone		
	ORDOVICIAN	Kimmswick Limestone Plattin Limestone Joachim Dolomite St. Peter Sandstone		Sylvan Shale Fernvale Limestone Viola Limestone Fite Limestone Tyner Formation Burgen Sandstone	Cason Shale Fernvale Limestone Kimmswick Limestone Plattin Limestone Joachim Dolomite St. Peter Sandstone		

Figure 7. Geologic and hydrogeologic units in the Ozark Plateaus study unit and adjacent areas (modified from Imes, 1990a)—Continued.

PALEOZOIC	ORDOVICIAN	Everton Formation Smithville Formation Powell Dolomite Cotter Dolomite Jefferson City Dolomite Roubidoux Formation Gasconade Dolomite Gunter Sandstone	Cotter Dolomite Jefferson City Dolomite Roubidoux Formation Gasconade Dolomite Van Buren Formation	Smithville Equivalent Powell Dolomite Cotter Dolomite Jefferson City Dolomite Roubidoux Formation Gasconade Dolomite Van Buren Formation	Everton Formation Smithville Formation Powell Dolomite Cotter Dolomite Jefferson City Dolomite Roubidoux Formation Gasconade Dolomite Gunter Sandstone Van Buren Formation	Ozark aquifer	Ozark Plateaus aquifer system
	CAMBRIAN	Eminence Dolomite Potosi Dolomite	Eminence Dolomite Potosi Dolomite	Eminence Dolomite Potosi Dolomite	Eminence Dolomite Potosi Dolomite		
		Derby-Doe Run Dolomite Davis Formation	Derby-Doe Run Dolomite Davis Formation	Derby-Doe Run Dolomite Davis Formation	Derby-Doe Run Dolomite Davis Formation	St. Francois confining unit	
		Bonneterre Dolomite Reagan Sandstone Lamotte Sandstone	Bonneterre Equivalent Reagan Sandstone Lamotte Sandstone	Bonneterre Equivalent Reagan Sandstone Lamotte Sandstone	Bonneterre Dolomite Reagan Sandstone Lamotte Sandstone	St. Francois aquifer	
PRECAMBRIAN IGNEOUS AND METAMORPHIC ROCKS						Basement confining unit	

Figure 7. Geologic and hydrogeologic units in the Ozark Plateaus study unit and adjacent areas (modified from Imes, 1990a)—Continued.